TEN YEARS OF SOLAR CHANGE AS MONITORED BY SBUV AND SBUV/2

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ABSTRACT

Observations of the Sun by the Solar Backscatter Ultraviolet (SBUV) instrument aboard Nimbus 7 and the SBUV/2 instrument aboard NOAA-9 reveal variations in the solar irradiance from 1978, to 1988. The maximum to minimum solar change estimated from the Heath and Schlesinger[1] Mg index and wavelength scaling factors is about 4% from 210-260 nm and 8% for 180-210 nm; direct measurements of the solar change give values of 1-3% and 5-7%, respectively, for the same wavelength range. Solar irradiances were high from the start of observations, late in 1978, until 1983, declined until early 1985, remained approximately constant until mid-1987, and then began to rise. Peak-to-peak 27-day rotational modulation amplitudes were as large as 6% at solar maximum and 1-2% at solar minimum. During occasional intervals of the 1979-1983 maximum and again during 1988, the dominant rotational modulation period was 13.5 days. Measurements near 200-205 nm show the same rotational modulation behavior but cannot be used to track long-term changes in the Sun because of uncertainties in the characterization of long-term instrument sensitivity changes.

INTRODUCTION

Since November 7, 1978, one week after the launch of the Nimbus 7 satellite, Solar Backscatter Ultraviolet (SBUV) instruments have been continually measuring the solar irradiance in the wavelength range from 160 to 400 nm. The original SBUV instrument aboard Nimbus 7 provided measurements from November 7, 1978 until February 13, 1987, when the chopper that was used to obtain an estimate of the dark current contribution to the observed signal began to go out of synchronization. The fraction of data with unacceptably high noise levels began to increase rapidly, until, by mid-March of that year, all the data were too noisy to be useful. Eight years of SBUV solar irradiance data have been archived at the National Space Science Data Center. The first in a series of SBUV/2 instruments was launched aboard NOAA-9 on December 12, 1984 and began solar measurements on March 12, 1985. These measurements continue to the present day. Unlike Nimbus 7, whose Sun-synchronous orbit passes over the ground near local noon, the original NOAA-9 orbit was launched into a 2:30 P.M. orbit. Since launch, the orbit has processed so that it now passes over the Earth at about 5:30 P.M. local time, so that at times the solar angle of incidence is outside the range for which the system was calibrated. In addition, at some times of the orbit, the solar detector is shadowed by other parts of the satellite. Data from March 12, 1985 to September 13, 1988 have been processed. Later data are still being reduced. A second SBUV/2 instrument aboard NOAA-11 began measurements in December, 1988, but these measurements also are still being reduced.

While the primary function of the SBUV instruments is to measure solar radiation backscattered by the Earth's atmosphere for the purpose of monitoring total column ozone and its vertical profile, the instrument can measure solar irradiance by deploying a diffuser plate into the optical path. The measurements of solar irradiance discussed in this paper are taken in a mode in which the instrument scans the solar spectrum between 160 and 400 nm. The bandpass is triangular, with a width of 1.1 nm. For SBUV, values are available at central wavelength intervals of 0.2 nm; for SBUV/2, the separation between adjacent points varies from approximately 0.154 nm at 160 nm to 0.137 nm at 400 nm.

RESULTS FROM NIMBUS 7 SBUV

Magnesium Index

The uncertainties in the characterization of the change of instrument sensitivity with time motivated the search for a measure of solar variability that would be independent of these uncertainties. To this end, Heath and Schlesinger[1] (hereafter HS) developed an index based on the ratio of the average irradiance over three wavelengths at the center of the Mg II 280-nm *h* and *k* doublet, which is not resolved by the instrument, to the average over four wavelengths, two each on either side in the far wings at local relative maxima of solar irradiance as a function of wavelength. The wing wavelengths were chosen to be at equal distances from the center; thus, use of this ratio eliminates not only any wavelength-independent changes in the instrument sensitivity, but also any wavelength-dependent changes with time that can be represented by a linear function of wavelength. Instrument characterization studies verify that the wavelength dependence of the changes can indeed be so represented at these wavelengths.

The lower panel of Figure 1 shows the Mg index as a function of time for the first 8 years of SBUV measurements. Short-term variability arising from rotational modulation is clearly apparent. HS found that although the period of rotational modulation was generally 27 days, corresponding to domination of the solar variability by a single active region, there were times when the period was 13.5 days, arising from two active regions on either side of the Sun. The Mg index had high values from launch until the end of 1983 and then declined gradually but not steadily until mid-1984, when it leveled off. Peak-to-peak 27-day rotational modulation amplitudes were as large as 6% at solar maximum, decreasing to 1-2% at solar minimum. The failure of rotational modulation to vanish entirely suggests that some residual activity persists even at solar minimum. The near constancy of the lower envelope for 1985-1987 suggests that days where the Mg index has its minimum value correspond to the least activity during a cycle. Also noteworthy is the fact that the Mg index is higher at rotational minimum during the period of solar maximum than at any time during solar minimum. This result implies that during solar maximum, even when the dominant active region is on the hemisphere that is turned away from the Earth, more activity is present on the visible hemisphere of the Sun than at solar minimum.

Scaling

HS showed that variations from 1978 through 1983 of the irradiance ratio across the Al edge near 210 nm (Kjeldseth Moe and Milone[2] have noted that the discontinuity in solar irradiance associated with the Al edge is at a longer wavelength than the laboratory edge; a possible explanation is overlap of many lines just longward of the true edge) could be reproduced by multiplying the variations of the Mg index by the ratio of the amplitude of rotational modulation at the Al edge to that of the Mg index. They used this result to derive a method for estimating solar variations at all wavelengths measured by SBUV. They selected 23 rotations with strong modulation in the Mg index. For each rotation, they derived the rotational modulation at every wavelength and the Mg index by calculating the ratio of the irradiance at maximum to the average over the two surrounding minima to eliminate the effect of changes in instrument sensitivity. For each wavelength, they derived a scaling factor by a linear fit to the 23 values of modulation as a function of the Mg index modulation, plus two points

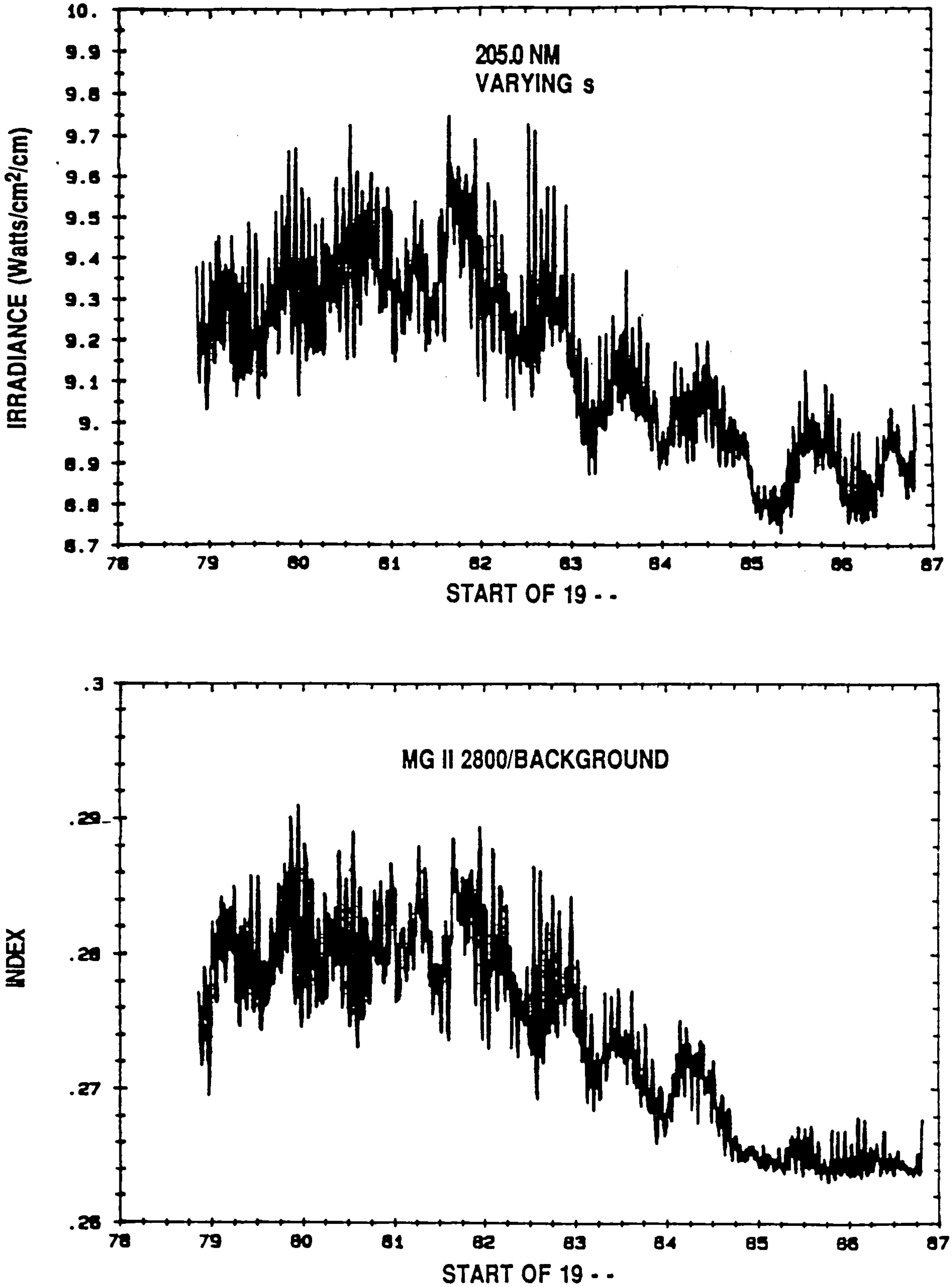


Figure 1. (top) Time series of solar irradiance at 205.0 nm using improved instrument characterization. (bottom) Time series of Mg index.

at no modulation, a ratio of 1. Using this method, solar variations between two days are estimated by multiplying the ratio of the Mg index for the two days by the scale factor for each wavelength.

To derive changes over the solar cycle, two 27-day periods were chosen: one during which the sustained values were near maximum, October 27 - November 22, 1979, and one near minimum, September 15 - October 11, 1986. Longer-term atmospheric changes will be sensitive to the sustained level of the solar irradiance rather than to extreme daily values. An additional constraint was that the two rotations be at the same time of year, to eliminate the effect of a 1% annual cycle in the later years of data probably arising from an imperfect correction for the angular dependence of the diffuser plate reflectivity.

The lower panel of Figure 2 shows the derived change. Longward of about 260 nm, the variation exceeds 1% only near the center of strong lines. From 210 to 260 nm, the change is on the order of 3-4%; it rises to 8% immediately shortward of the Al edge near 210 nm and to 10-11% at 180 nm. At wavelengths shorter than 170 nm, the signal is too weak and the data are too noisy to derive useful results.

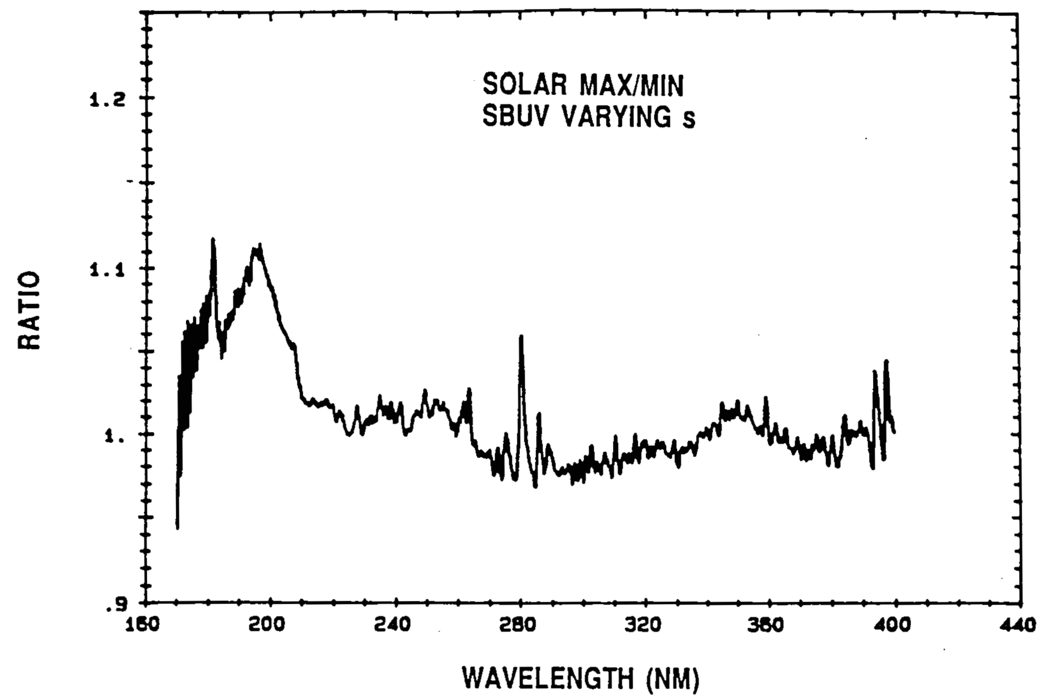
Improved Instrument Characterization

Schlesinger and Heath[3] and the User's Guide to the solar irradiance tapes[4] have shown that not all instrumental effects have been removed from the archived SBUV solar irradiance values. Cebula *et al.*[5] and the User's Guide describe how instrument changes were characterized in producing the archived data. Wavelength-dependent degradation was assumed to be proportional to two exponential decays, one with diffuser exposure, and one with time. The decay rates were derived by a fit to the data for an interval during 1980-1981. This interval was selected because exposure was not linear with time and overall degradation was dominated by the exposure-dependent term. Rotational modulation was removed, and the total elapsed time was sufficiently short that long-term solar change would be small compared to the instrumental effects. The same method has since been applied to derive the degradation rate at one period during 1984 and one during 1986. While the decay parameter for exposure agrees to within the errors for all periods, the fits suggest that the time-dependent degradation rate increased between 1981 and 1984. This additional degradation implied by the change in the time-dependent decay parameter has the same magnitude and wavelength dependence as the instrumental component estimated to remain in the archived data.[4] A new instrument characterization has been derived by Schlesinger and Cebula,[6] assuming that the increase in time-dependent decay derived from the fits represents the true instrument behavior.

The upper panel of Figure 1 shows the time series at 205 nm, chosen because of its importance to stratospheric chemistry. Fortuitously, the variations at this wavelength have a scale factor close to unity and thus are predicted to be approximately equal in percentage amplitude to the SBUV Mg index variations shown in the lower panel. Both plots are on a scale with a range of approximately 14% from top to bottom. With the new characterization, the observed variations at 205 nm show the same overall short-term and long-term patterns as those of the Mg index. An additional 1% amplitude annual cycle is believed to be of instrumental origin.

The upper panel of Figure 2 shows the ratio of irradiances derived using the new characterization for the periods used to represent solar maximum and minimum in the Mg index estimate shown in the lower panel. The solar cycle variation on the figure is approximately 5% immediately shortward of the Al edge, and about 1% from 210 to 260 nm. However, around 290 nm, the plot shows the irradiance to be 2% *lower* at solar maximum than at solar minimum. Measurements of the solar constant, representing longer wavelengths,[7] show higher irradiances at maximum, indicating that the overall change is dominated by bright active regions. The dominance of the bright regions becomes even more pronounced at the shorter wavelengths.[8] Thus, the difference at 290 nm is probably a residual instrumental change. If we assume that this instrumental effect persists at shorter wavelengths, then the derived change must be increased by 2%, to 3% at 210-260 nm and 7% just shortward of the Al edge. These values are in excellent agreement with the Mg index estimate.

The structure near the Mg II h,k and Ca II H,K doublets is the result of wavelength drift and jitter. In the wings of these strongest lines where the irradiance changes steeply with wavelength, even a small change in the wavelength can lead to a noticeable change in irradiance. The variations shortward of 200 nm probably include a large component arising from limitations of the instrument characterization scheme at these wavelengths.



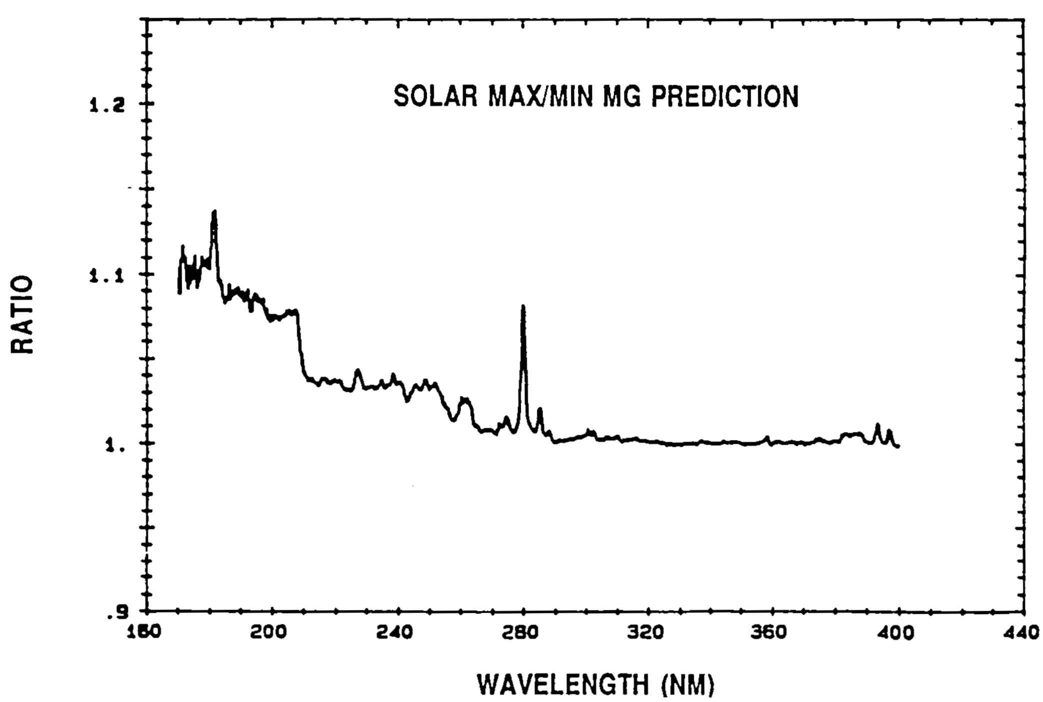


Figure 2. Ratio of solar irradiances at solar maximum (October 27 - November 22, 1979) to irradiances at solar minimum (September 15 - October 11, 1986). (top) Direct measurements using improved instrument characterization. (bottom) Estimated from Mg index.

RESULTS FROM NOAA-9 SBUV/2

Magnesium Index

For the NOAA-9 SBUV/2, the irradiances at wavelengths in the wing of the Mg doublet are, by an unfortunate chance, measured at the lowest signal for the lowest gain range and consequently have noise of about 2-4%. This problem was recognized before launch. Consequently, the Mg index for SBUV/2 is measured using a special mode with measurements at carefully selected wavelengths; results of these measurements are being reported by Donnelly.[9] However, use of running averages reduces the noise sufficiently that long-term trends and qualitative features of the rotational modulation can be examined.

Figure 3 shows the results of applying a 5-day boxcar running average to the SBUV/2 Mg index derived from the scans. The plot shows the overall constancy near minimum through 1985 and 1986 seen in the Nimbus results, the beginnings of a rise in spring 1987 (just after the failure of the SBUV chopper!), and a much steeper rise starting at the beginning of 1988. The rise from minimum has been about 4-5%. Note that these results have not been plotted on the same graph as the SBUV Mg index. That choice is deliberate. The wavelengths measured to derive the Mg index for SBUV/2 are not exactly the same as for SBUV; furthermore, the Mg index derived from the discrete measurements uses slightly different wavelengths than those from the scans. The three index values will be different even for simultaneous measurements; compare the 1985-6 values in Figures 1 and 3. If one wishes to generate a single Mg index plot, the relation among the Mg indices from the different measurements must first be derived. In addition, in order to apply the HS scaling technique, either the index from the new measurement must be converted to the SBUV value, or the scale factors must be derived independently for the new index. Efforts in this direction are under way.[10]

Figure 3 also shows the presence of rotational modulation of the Mg index; however, the detailed structure is modified by the averaging procedure.

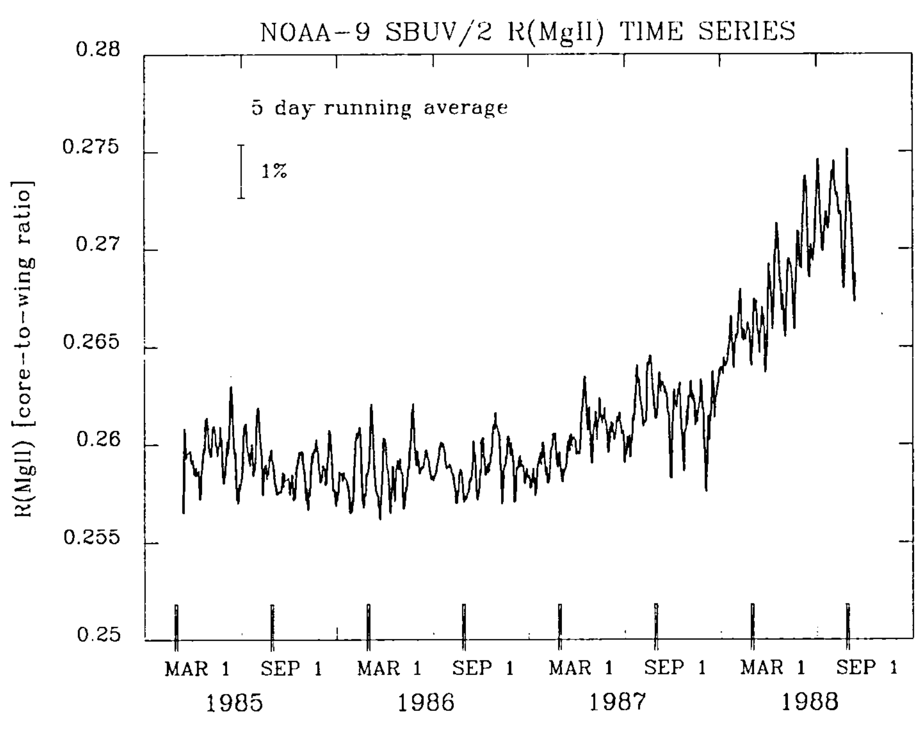


Figure 3. Five-day running average of Mg index derived from SBUV-2 sweep mode measurements.

Direct Measurements

Rotational modulation can be examined by direct examination of the measurement values at shorter wavelengths. In the raw measurements, there is a day-to-day variation, nearly independent of wavelength, in the sense that the data appear to be in one of two discrete "states", one with a higher value and one with a lower value. The most likely origin is a 0.25° non-repeatability in the discrete-valued diffuser plate deployment angle. The Mg index, as noted earlier, would not be affected by such a variation. To eliminate this effect in the values for individual wavelengths, the irradiances at 391.3 nm, a wavelength at which solar variability is expected to be less than 0.2% long-term and 0.5% short-term, are used to identify days with anomalous values. Values on these days are corrected by decreasing them by 1.3%. Preliminary data show that this problem has been eliminated for NOAA-11.

Figure 4 shows the irradiance at 202.2 nm with the anomalous values corrected. An inset contains the data for 1988 with dashed lines appearing at 27-day intervals on the abscissa to show the rotational modulation more clearly. The most striking feature is that the period is 13.5 days, one-half rotation, during much of this period of the rise to maximum. The amplitudes are about 2%. Combined with the Nimbus measurements, this result shows that rotational modulation can be at half the rotation period at any time during solar maximum -- rise or decline.

Because a characterization of the changes with time of the instrument sensitivity has not yet been defined, the long-term change in Figure 4 should not be regarded as describing the actual solar variations. However, it is interesting that the pattern changes from a gradual decline to a steady rise early in 1988, the time when the Mg index shows a sharp increase in solar activity. The magnitude of the increase is what would be expected if the SBUV scaling factors were applied and there were no sudden changes in the pattern of instrument sensitivity change.

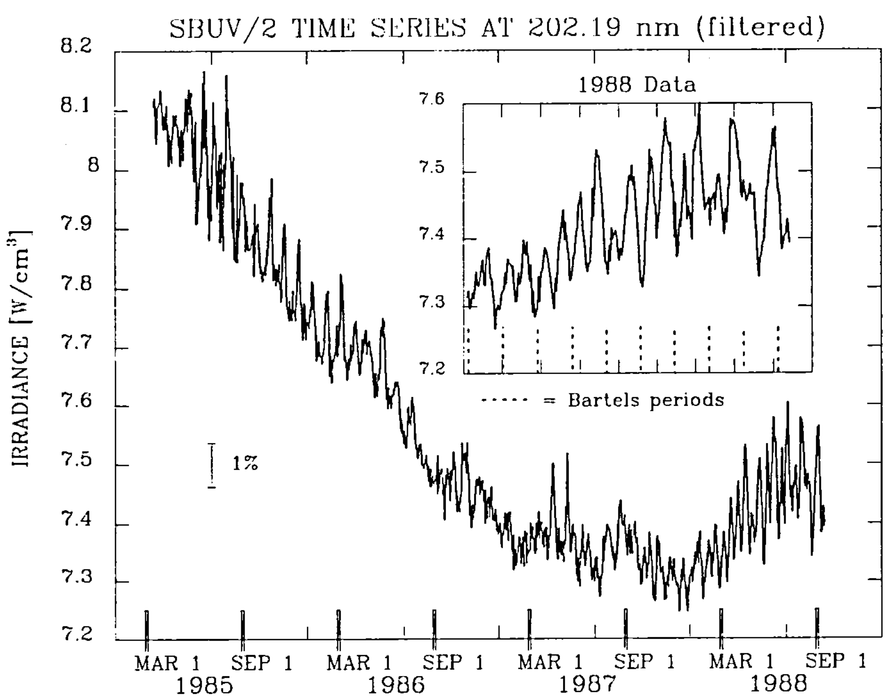


Figure 4. Irradiance measurements at 202.2 nm from SBUV/2. (inset) Values for 1988.

CONCLUSIONS

The Heath and Schlesinger[1] Mg index provides a powerful tool for estimating monitoring solar variability in the near ultraviolet and interpreting the direct measurements. Solar irradiances were high from late 1978 until 1983, declined until early 1985, remained constant until mid-1987, and then began to rise. Time spans when the rotational modulation period was 13.5 days occurred during and after the peak of cycle 21 and during the rise of cycle 22. Using the Mg index and direct measurements reduced using an improved characterization for changes in instrument sensitivity, variations from solar maximum to minimum of cycle 21 have been derived. Near 200 nm, the estimated variation is 5-8%; for 210-260 nm, the estimate is 1-4%, with the higher values in the range favored for both cases. Because the Mg indices measured by different instruments are not identical and must be transformed to a common scale, there should be a significant period of overlap between consecutive instruments measuring the solar ultraviolet if continuity of values is to be maintained.

ACKNOWLEDGEMENTS

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